CLASSIFICATION OF SELECTED METEORITES

BASED ON

FAYALITE CONTENT OF THEIR OLIVINE

MAY 30, 1972

NELSON SHAFFER

Approved 6/72
George E. Moore Jr

Abstract

The importance of classifying is discussed, and a history of meteorite classification emphasizing the Prior - Mason chemical classifaction, and the Van Schmus and Wood chemical and petrologic grid is presented. Data on the fayalite content of olivine from eleven meteorites is given and used to classify these meteorites.

Introduction

Classification of materials and phenomena is one of the basic goals of science. The skill of placing several related things into a group and finding small but significant differences between members of this group thus enabling subtle relationships between these members to be clearly manifested is at the heart of learning. A good classification should be based on significant criteria for division which allow rational systematization of the classes they define. The classification of meteorites is a good example of the evolution and fruition of the search for good criteria and logical systematization of facts that leads toward the covering of possible mechanisms that act to cause the difference observed. If one assumes that knowledge properly ordered leads to increased understanding, classification becomes a useful tool for expanding present knowledge. Several meteoriticists have used this assumption to propose ideas about the origins and structures of planets leading from new criteria for classifying meteorites.

History of Classification

Shortly after the extraterrestial orgin of meteorites was "officially" accepted by the scientific community with the publication of Biot's (1807) description of the L'Aigle, France fall, the basic distinction between stony and iron meteorites was recognized by Klaproth. This division was extended by Gustav Rose (1863) by dividing the irons into pallasites or true irons, and mesosiderites with many silicate inclusions, and the stones into chondritic that contained spherical bodies called chondrules and non chrondritic stones in which chonrules were absent. N.S. Maskelyne (1883) suggested that mesosiderites should be made into a class equal in rank to irons and stones. At this stage the three basic subdivisions, still used today, had been recognized as valid criteria for the division of "stones from the sky" into; irons or siderites made mostly of nickel-iron, siderolite or stony irons consisting of about equal amounts of nickel-iron metal and silicates, and aerolite or stones made mostly of silicates.

Tschermak took the next step by dividing the irons into sub-classes based on the presence of Widmanstatten structure and width of Kamacite bands, which proved to be a valid criteria for classification, and he also subdivided chondrites on the less useful basis of color. A. Brezina compounded this error by using criteria such as color, state of fusion crust, venation, and brecciation. The end product of this stage of development was the unwieldy Rose - Tschermak - Brezina classification made up of two subdivisions with a staggering total of seventy six sub-classes which was in general use until about 1920 when G. T. Prier (1916, 1920) pointed out that this system, being based on superficial characteristics, was of limited value and he offered a system based on the chemical similarities exhibited by meteorites. He observed a regular relationship of nickel content to nickel-iron and to iron in silicate phases that he stated as follows:

TABULAR CLASSIFICATION OF METEORITES.

← Class	Group →	1	2	3	4
	Nickel-iron →	Fe : Ni = 13 and over.	Fe : Ni = 13–8.	Fe : Ni = 8–2.	—
	Magnesium silicates →	Enstatite (and Clino-enstatite). MgO : FeO very high to ∞.	Bronzite (and Clino-bronzite) and Olivine. MgO : FeO over 4.	Hypersthene (and Clinohypersthene) and Olivine. MgO : FeO = 4–2.	Pyroxene (mostly monoclinic) and Olivine. MgO : FeO less than 2.
	Felspar →	Oligoclase.	Oligoclase.	Oligoclase.	Anorthite.
IRONS. 1	SIDERITES → Mainly nickel-iron.	Nickel-poor Ataxites. Hexahedrites. Coarsest Octahedrites. Coarse Octahedrites.	Medium Octahedrites to Finest Octahedrites.	Some Finest Octahedrites? Nickel-rich Ataxites.	Oktibbeha County?
STONY-IRONS. 2	SIDEROLITES[1] → Nickel-iron in large amount.		Most Pallasites. Siderophyre. Lodranite. Mesosiderites.[2]	A few Pallasites.	
STONES (AEROLITES). 3	CHONDRITES → Nickel-iron generally in decreasing amount from left to right.	*Enstatite-chondrites.* Daniel's Kuil (Hvittis) type.	*Bronzite-olivine-chondrites.* Kroonstad type.	*Hypersthene-olivine-chondrites.* Baroti and Soko-Banja types.	
STONES (AEROLITES). 4	ACHONDRITES → (Non-chondritic stones). Nickel-iron in small amount or absent.	*Enstatite-achondrites.* Aubrites (Aubres, Bishopville, and Bustee).	*Clinobronzite[3]-olivine-achondrites.* Ureilites.	*Hypersthene-olivine-achondrites.* Amphoterites (& Rodites). *Hypersthene-achondrites.* Diogenites (Shalka, &c.). *Olivine-achondrites.* Chassignite.	*Calcium-rich Achondrites.* Angrite, Nakhlite. Eucrites, Shergottite, Howardites. Mesosiderites.[2]

[1] As defined by Maskelyne, including both the lithosiderites and siderolites of Brezina.

[2] As seen in the vacant compartments, the stony-irons (Class 2) and the calcium-rich achondrites (Group 4) fit less perfectly than the rest into the general scheme, and mesosiderites appear to be related to both, for as regards iron and olivine they belong to Group 2, and as regards pyroxene and felspar to Group 4.

[3] See p. 56.

Table I (Prior 1920)

"The less the amount of nickel-iron in chondritic stones the richer it is in nickel and the richer in iron are the Mg silicates"

From this relation, known as Prior's rules, he postulated a genetic relationship for meteorites by which all come from one melt that underwent progressive oxidation to yield the different types of meteorites observed. Prior's classification is given in Table 1.

Mason (1962a) revised Prior's classification by adding the olivine-pigeonite group and carbonaceous group with two subgroups. He also suggested using fayalite content of olivine to define chondrite groups as follows; enstatite chondrites showing no olivine, olivine-bronzite chondrites having olivine with Fa 14 - 22%, olivine - hypersthene chondrites containing olivine with Fa 23 - 32%, olivine - pigeonite chondrites containing olivine with Fa 30 - 40%, carbonaceous chondrites of two types with type I having no olivine and type II with nearly pure fosterite. The olivine pigeonite group was made a third type of carbonaceous chondrite due to close similarites in overall chemistry (especially relatively high carbon and volatile content) of all three as shown by Wiik (1956). The final form of this revised classification is given in Table II.

Although Prior's classification as modified by Mason is the most widely used today, in recent years several alternant classifications have been proposed, based on finer distinctions revealed by more comprehensive and detailed studies. Urey and Craig (1953) compiled many superior chemical analysis, and made a plot of iron in the metallic sulfide phases against the iron in silicate phases, and found two distinct groups in the chondrites could be distinguished. They called these the H and L groups (Fig. 1) for high and low groups with total iron content of 28.58% and 22.3% respectively. Each of these groups follow Prior's rules.

TABLE II *

Irons

Hexahedrites - nickel 4 - 6% no structure

Octahedrites - nickel 6 -14% shows Widmanstatten pattern

coarse - nickel 6 - 8% kamacite[1.)] bands 1.5 - 2.5mm

medium - nickel 7 - 9% kamacite bands .5 - 1.5mm

fine - nickel 8 -14% kamacite bands less than .5mm

Nickel Rich Ataxites - nickel less than 12% no structure

Stony Irons

Palasites - nickel-iron and olivine in about equal amounts

high iron - metal 55%,silicate 45%,nickel 10% Fa 13

low iron - metal 30-35%,silicate 65-70%,nickel 15% Fa 19

Sideraphyre - only one meteorite, nickel-iron about 50%, orthopyroxene plus tridymite about 50%

Lodranite - only one of this type, a friable aggregate of granular olivine and orthopyroxene in nickel-iron matrix each phase in about equal amounts

Mesosiderites - nickel-iron not continuous matrix but dispersed in silicate matrix of pyroxene and plagioclase

* Modified from Mason (1962b)

1.) nickel poor iron with body centered cubic structure

TABLE II (cont.)

Stones

Chondrites - show chondrules

enstatite - no olivine present, high metal content

olivine-bronzite - olivine with Fa 15 - 22%

olivine-hypersthene - olivine with Fa 22 -32%

carbonaceous - blacr color,friable,low density,high carbon,water, and sulfur content

typel - have no chondrules and no olivine

type 11-have chondrules and olivine with Fa 0 -15%

typeJ11 - have chondrules and olivine Fa 30 -40%

Achondrites - have no chondrules, little nickel-iron, based on mineralogy which reflects chemical composition

Calcium Poor - CaO 0 -3%

enstatite or aubrites - $FeSiO_3$ 0 -6%

hypersthene or diogenites - $FeSiO_3$ 20- 35%

olivine or chassignite - only one, made of olivine

olivine-pigeonite or urelites - $FeSiO_3$ 48 - 66%

Calcium Rich - CaO 5 -25%

augite or angite - only one

diopside-olivine of nakhlites - olivine Fa 66%

Pyroxene-Plagioclase - $FeSiO_3$ 29 -66%

eucrites - pigeonite and anorthite $FeSiO_3$ 48-66%

howardites - hypersthene and anorthite $FeSiO_3$ 29-30%

Urey suggested from this that two parent bodies were involved in the formation of meteorites. F. C. Leonard (1956) proposed a classification that divided Prior's major subgroups into thirty subclasses based on detailed mineralogical study. Although he used ten varieties of pyroxenes and six varieties of plagioclase no attempt was made to use olivine to define these classes. Further criticisms of his systems are that detailed mineralogy is not known for most meteorites and his boundaries are arbitrary.

The Russian, Yavnel, (1960) assuming several parent bodies, set forth a chemical classification with Prior's main subclasses. He extended Prior's rules to Prior's "Group" rule based on chemical analysis, which took cognizance of Urey and Craig's findings. This "group" rule says that Prior's rules do not hold within a single chondrite group but are valid for the relation between major groups through the whole system, from group to group, including the irons. The implication of his group rule is that at an early stage in the planet nebula, when much interaction of phases was common, Prior's rules held, but with progressive differentation and formation of discrete groups (for which Prior's rules do not work) the phase interactions became restricted and the mechanisms producing adherence to Prior's rules broke down. Yavnel added high and low nickel-iron subgroups to pallesite and mesosiderite groups to show Prior's rules worked for stony irons as well as chondrites. He also broke the chondrites into calcium rich and calcium poor subgroups.

Van Schumus and Wood (1967) combine chemical composition and petrologic types as criteria for a classification of chondrites that seek to place meteorites on a two dimensional grid showing chemical differentation and degree of equilibration of crystalization. They use Urey's and Craig's H and L groups which correspond to Mason's olivine

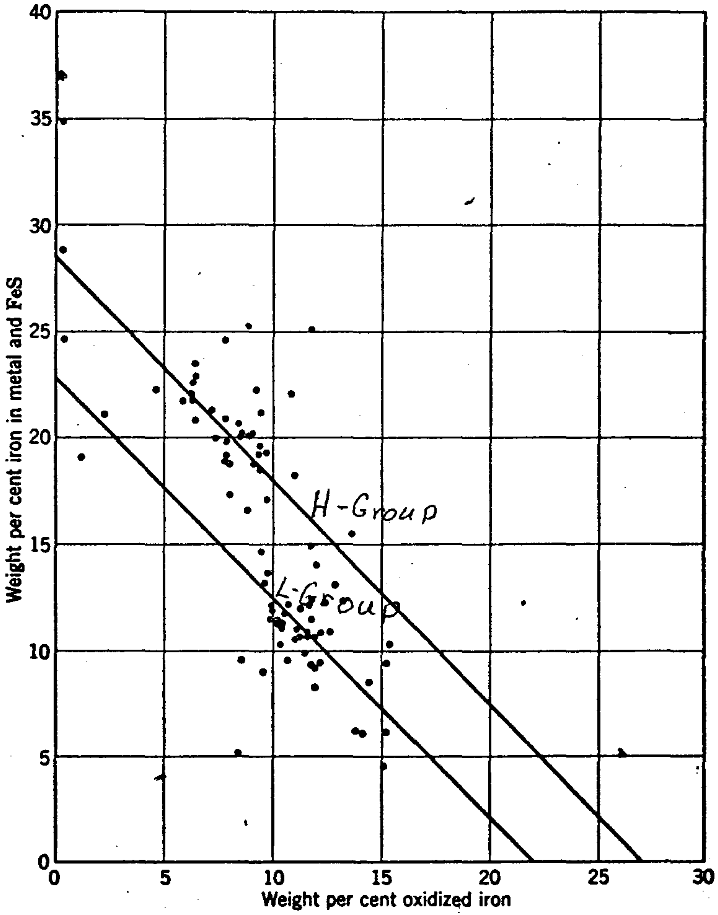

Fig. 28. Relationship between oxidized iron (present largely or entirely as ferromagnesian silicates) and iron as metal and sulfide in 94 selected analyses of chondritic meteorites (Urey and Craig, 1953). Fig. 1

bronzite subgroup and add E,LL and C groups which are equivalent to Mason's enstatite, olivine hypersthene, and Wiik's carbonaceous subgroups respectively to show chemical relations. The conditions of crystallization are defined by six petrologic types which are defined by the following criteria:

I - No chondrules high amounts of volatiles

II - Olivine and pytroxene variable, much matrix, clinopyrexene greater than orthopyrexene, chondrules and nickel sulfides, moderate amounts of water and cargon

III - 75% mean deviation olivine, igneous glass in chondrules, good chondritic texture, nickel sulfides present

IV - Good chondrules, olivine and pyroxene, uniform composition, some recrystalization of chondrules, clinopyroxene are greater than orthopyroxene

V - Olivine and pyroxene homogeneous, mostly orthopyroxene, no plagioclase

VI - Recrystalized primary structures obliterated, plagioclase present

Optical Technique and Data

Mason (1962a) suggested using the fayalite content (in molecular percent) of olivine as an improved criteria for assigning chondrites to one of Prior's subclasses. The previously used criteria, namely:

1) MgO/FeO ratio found from bulk analysis

2) MgO/FeO ratio of HCl insoluble silicates

3) Fe/Ni ratio and amount of nickel-iron

had several drawbacks such as difficulty of analysis and difficulty of obtaining accurate results due to the weathering of the irons. Mason

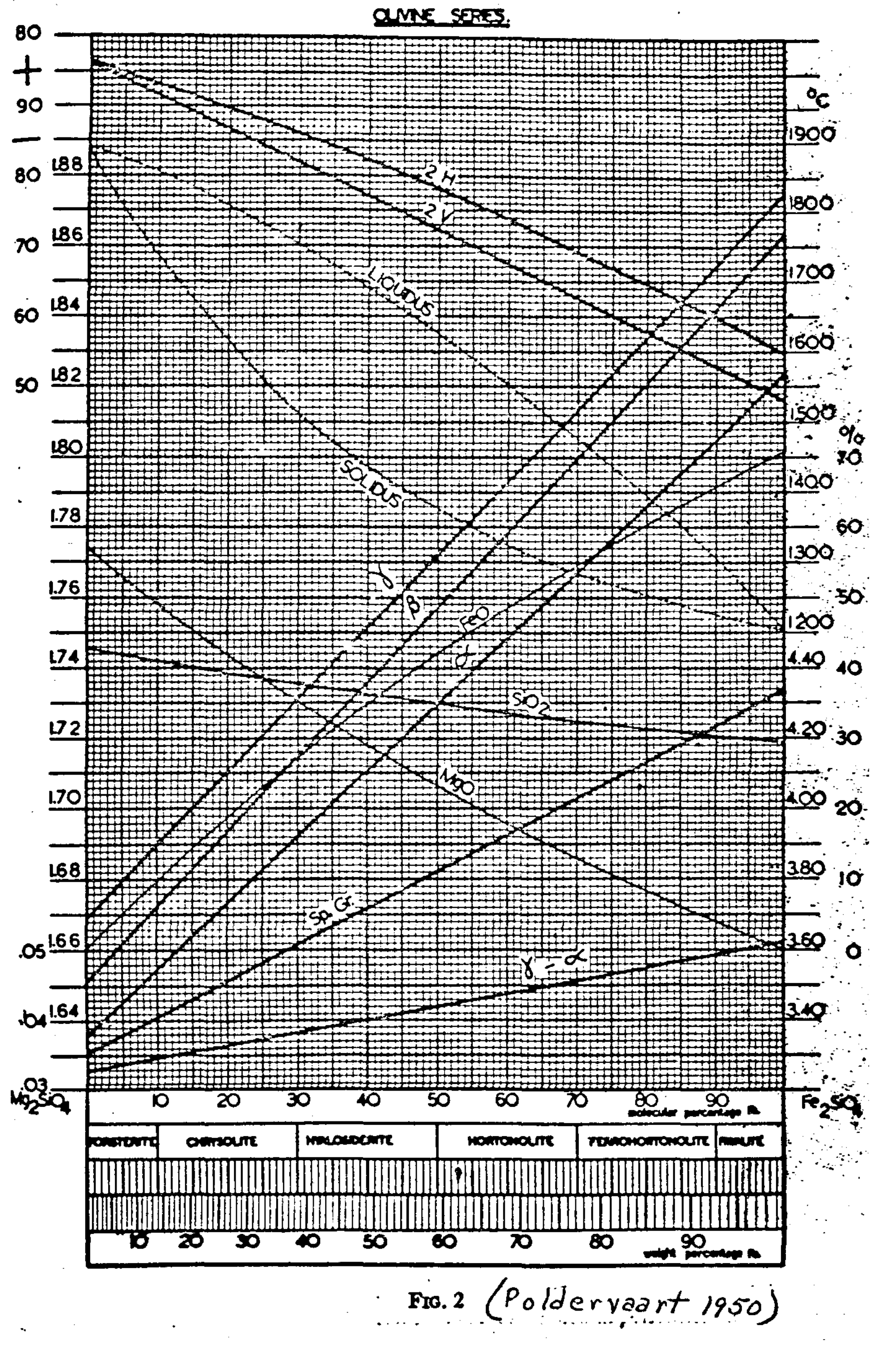

FIG. 2 (Poldervaart 1950)

chose olivine, which is present in almost all chondrites, because it does not weather earily, the composition varies simply between forsterite and fayalite, and this composition can be easily determined by index of refraction optically and finding the corresponding fayalite content from a chart, (see Fig. 2), showing the variation of physical properties with chemical composition of the olivine solid solution series, developed by A. Poldervaart (1950). This method is quick, inexpensive, requires very small amounts of sample, (even less than for x-ray work), and accurate. Mason places the accuracy of this method at ± 1% Fa. Although Keil and Fredrickson (1964) claim only ± 5-10% Fa accuracy, Wahlstrom (1960) states that index of refraction can be measured to ± .002 with the immersion method using monchromatic light, carefully standardized oils and orientated fragments. This corresponds to Mason's ± 1% Fa accuracy. Since a universal stage was not used to orient the fragments the accuracy of my results is less than the optimum 1%. This inability to orient grains perfectly was somewhat overcome by giving greater weight to I.R. measured for grains which showed nearly centered optic axis figures. I estimate the accuracy of my results to be ± 3-5% Fa.

The samples were crushed and sieved through a 100 mesh screen and the portion caught on the 120 mesh screen (according to Kerr, 1959) was used for index of refraction measurements. The crushed grains were observed with a Leitz SM - POL polarizing microscope using monochromatic sodium light and standard immersion mount technique (Walhstrom 1960). The results are given on Table III. Sample locations and texture descriptions are given in Table IV.

TABLE IV [1]

NAME AND LOCATION	DATE	DESCRIPTION
Admire, Lyn Co., Kansas	Found 1881	Pallasite olivine with some iron or iron sulfides included
Brenham, Kiowa Co, Kansas	Found 1882	Pallasites olivine showing various colors
Dora, Roosevelt Co, New Mexico	Found 1955	Pallasite olivine with some pyroxenes
Springwater, Saskatchewan, Canada	Found 1931	Pallasite very clear yellowish olivine
Allende, Mexico	Fell 2/8/1969	Black friable carbonaceous chondrite with some nickel-iron
Murchison, Australia	Fell 9/28/1969	Black friable carbonaceous chondrite with chondrules of olivine and irregular glass grains
New Concord, Muskingham Co., Ohio	Fell May 1,1890	Gray-white friable showing brown chondrules prominent nickel-iron
Plainview, Hale Co.,Texas	Found 1917	Brown to black with small chondrules and metal
Plainview, Hale Co., Texas	Recognized 1950	Brown to black with small clear brown chondrules
Potter, Cheyenne Co., Nebraska	Found 1941	Brown friable with dark chondrules and nickel-iron
Tell, Childress Co., Texas	Recognized 1965	Dark brown with lighter chondrules

1) Locations and dates taken from Hey 1966

TABLE III

SAMPLE NAME	γ	β	Fa%	CLASSIFICATION PRIOR-MASON		VANSCHMUS
Admire	1.71	1.69	Fa 18	Pallasite Low Fe		
Brenham	1.71	1.69	Fa 18-20	Pallasite Low Fe		
Dora	1.72	1.69+	Fa 20-22	Pallasite Low Fe		
Springwater	1.70	1.68	Fa 15	Pallasite High Fe		
Allende	1.74+	1.72+	Fa 32	Carbonaceous	III	C-3
Murchison	1.70	1.69-	Fa 15-18	Carbonaceous	II	C-2
New Concord	1.72	1.70+	Fa 23	Olivine-Hypersthene		L-6
Plains	1.70+	1.69	Fa 19-20	Olivine-Bronzite		H-5
Plainview	1.71	1.69	Fa 20	Olivine-Bronzite		H-5
Potter	1.72	1.70	Fa 25	Olivine-Hypersthene		L-6
Tell	1.72	1.69	Fa 18	Olivine-Bronzite		H-6

A
GMoore

X-ray Techniques and Data

The mole percent Fa can also be determined by s-ray diffraction of the d spacing since increasing iron content causes the unit cell of olivine to increase. The general method used to determine Fa% is that developed by Yoder and Sahama (1957)in which 2θ of the 130 reflection found by an x-ray diffractometer is used to find d 130 which can be related to the x-ray determination curve they made from data obtained with chemically analysed olivines. The curve has a formula Fa (molecular % = 4233.91 - 1494.5 d 130.

This method uses a finely ground powder mounted in an x-ray powder camera. This sample is rotated and is radiated with monochromatic x-rays to produce a film record. The 2θ of the 174 line is measured and d spacing of 174 planes if found by calculation or from charts. Fosterite content can then be found by the formula Fa (molecular % = 4151.46 - 3976.45 xd 174.

Iron $K\alpha$ radiation produced by a Norelce x-ray machine was used. The samples were mounted in a 28.65mm Debeye - Schere powder camera with Straumanis film mount. Films were measured to an accuracy of $\pm$ .005 mm on a Norelco light box. The x-ray determinations of fayalite content is given in Table V.

Conclusions

My findings fit nicely into Mason's revised version of Prior's classification. Similar but more extensive data have been used to argue, not unopposed, that all meteorites are derived from a single parent mass, of carbonaceous chondrite composition that has been progressively reduced (Mason 1962b). Couples with chemical analysis for nickel-iron similar data have been used to uphold Prior's rules.

TABLE V

NAME	2θ [1)]	d 174	Fa%
Admire	142.22	1.0231	16.83%
Brenham	142.10	1.0235	18.42%
Dora	141.51	1.0252	25.2%
Springwater	142.17	1.0232	17.23%

1) corrected for film shrinkage

Acknowledgements

I gratefully acknowledge the help of Dr. George E. Moore, Jr. who acted as advisor for this thesis, Dr. W. R. Foster who made samples available and introduced me to the field of meteoritics, Dr. H. E. Wenden who offered invaluable assistance and guidance during the x-ray investigation, and Dr. Wayne J. Walton who donated several samples and offered moral and technical support.

References

Biot, J. (1807) Report of the Comission Investigating the L'Argile Meteorite Fall French Acadmy of Science

Hey, Max H. (1966) Catalogue of Meteorites Third Edition Alden Press Oxford, Great Britain

Jambor, J. & Smith, C. (1964) "Olivine Composition Determination with Small-Diameter X-ray Powder Cameras" Mineralogy Magazine Vol. 33 pp. 730 -741

Keil, K. & Fredriksen, (1964) "The Iron, Magnesium, and Calcium Distribution in Coexisting Olivines and Rhombic Pyroxenes in Chondrites" Journal of Geophysical Research Vol. 69 pp.3487 - 3515

Kerr, Paul (1959) Optical Mineralogy Third Edition Mc Graw Hill

Leonard, F.C. (1956) "A Classification Catalogue of Meteoritic Falls of the World" University of California Publish Astronomy Vol. 2 pp.1 - 80

Mason, Brian (1962a) "The Classification of Chondritic Meteorites" American Museum Novitates 2085

(1962b) Meteorites John Wiley & Sons, Inc New York

(1963) "Olivine Composition in Chondrites" Geochim et Cosmochim Acta Vol. 27 pp.1011 -1023

Poldrevaart, A. (1950) "Correlation of Physical Properties and Chemical Composition in Plagioclase, Olivine, and Orthopyroxene Series" American Mineralogy Vol. 39 pp.693 - 737

Prior, G.T. Second Revised Edition by Hey, Max H. (1953) Catalogue of Meteorites British Museum London

Prior, G.T. (1916) "On the Genetic Relationships and Classification of Meteorites" Mineralogy Magazine Vol. 18 pp.24 - 44

(1926) The Classification of Meteorites" Mineralogy Mazine Vol. 19 pp.51

Rose, G. (1863) "Beschreibung und Eintheilung der Meteoriten .... im Mineralogische Museum zu Berlin" Physik Abhand Akad Wiss. Berlin pp.23 - 161

Urey, H. & Craig, H. (1953) "The Composition of the Stone Meteorites and the Origin of Meteorites" Geochim et Cosmochim Acta Vol. 4 pp.36 - 82

Van Schmus, W.R. & Wood, J.A. (1967) "A Chemical - Petrologic Class for the Chondritic Meteorites" Geochim et Cosmochim Acta Vol. 31 pp.747 - 765

Wahlstrom, Ernest (1969) Optical Crystalography Forth Edition John Wiley & Sons, Inc.

Wiik, H. (1956) "The Chemical Composition of Some Stony Meteorites" Geochim et Cosmochim Acta Vol. 9 pp.279 - 289

Yavnel, A. (1960) "Classification of Meteorites According to Their Chemical Composition" Int. Geology Review Vol. 2 pp.380 - 397

Yoder, H.S. & Sahama, T. (1957) "Olivine X-ray Deturmination Curve" American Mineralogist Vol. 42 pp.475 - 491

no author (1950) Tables for Conversion of X-ray Diffraction Angles to Interplanar Spacing U.S. Department of Commerce